

Quality Controls and Security Features for U.S. Currency and Postage Stamps

Max Grimsley , James Hess , Mark Poulsen , Ken Rankin , David Curtis
United States Department of the Treasury, Bureau of Engraving and Printing
Washington, D.C. 20228

Abstract

The U. S. Bureau of Engraving and Printing produces over 9 billion Federal Reserve notes per year. Each note must maintain uniform consistency for both security features and print quality. The quality control process necessary to assure the uniform nature of U.S. currency requires a significant multi-tiered approach. Based on innovative optoelectronic techniques, individual security features are examined as a critical element during each phase of the production process. Print quality standards must also be strictly maintained and monitored to assure the uniformity of the most popular printed item in the world. This presentation describes the approach and some of the techniques developed and implemented in-house to carry out the necessary monitoring and control.

Keywords: Watermark, Inspection, Neural Network, Computer Vision,

1. Introduction

The United States Bureau of Engraving and Printing has recognized the need to establish a group whose primary mission was to keep abreast of and implement emerging technologies as they related to the production of U.S. currency and postage stamps. The primary goal of this group is the development of inspection systems and techniques for visual and non-visual features in the production process. A secondary goal is the improvement of existing techniques and methods by integrating new technologies while optimizing the process and eliminating dated equipment. Additionally this group also develops new equipment and systems that automate processes that are currently rate-limiting in the BEP's mission.

This manuscript highlights two of the systems that this advanced automation group has developed. These systems examine and analyze in detail specific security features of U.S. currency. This text shows an in depth look at the fiber formation of the watermarks and their level of acceptability. Additionally this text explains how the security thread is examined to meet the tolerances and specifications associated with this feature. Lastly is an overview of an inspection system used to examine a semi-covert feature incorporated into federal reserve notes. Along with these systems, this group is presently working to develop new systems, which will maintain and control the quality of security features for United States currency.

2. Watermark and Security Thread Analysis

Security threads and portrait watermarks are readily recognizable overt security features for U.S. currency. It is essential that these security features maintain a uniform consistency. In conjunction with a private contractor, the BEP has developed a stand-alone transmissive image-capturing system for sheet-by-sheet examination of blank currency paper. This system utilizes a neural net pattern-matching algorithm that compares the captured image to an acceptable composite standard reference image. The reference is a synthesized image that was created by enhancing and smoothing a composite of several authentic watermarks. For transmissive inspection of security threads, the edges of the thread are found and a software caliper is used to determine whether the thread is within its specific tolerance window.

The development of this system was required to enable the BEP to better monitor and control watermark and security thread features. The ability to collect this information was essential in establishing a quality control plan. Additionally this information is necessary, to assure that the criteria and tolerances involved in the currency paper manufacturing process, are being met.

2.1. Hardware

Two standard RS-170 cameras, 640 x 480, are used to acquire each type of image. One camera examines the threads and one examines the watermark. Both cameras have similar specifications, but vary in physical size. This application uses a 1/2" B/W CCD camera and a 2/3" B/W CCD camera. These cameras have high sensitivity and low light imaging capabilities and use a 35mm flat field lens. Because of the compact size of these cameras both the thread and the watermark can be captured and analyzed simultaneously.

The frame grabber board that was chosen for this application integrates well with the software, and can support two cameras from multiple I/O triggers. Additional features are high-speed, low-cost, 8 bits-per-pixel monochrome. Bit level control of the I/O triggers and the serial port provides for real-time control.

The host computer is a standard 400MHz Pentium II PC with 128mb of RAM. This host computer and other elements of this system were chosen because they are readily available and quickly interchangeable. Each of these items can easily be acquired and replaced in the event of failure.

The light source selected for this application is a 150-watt regulated, low voltage light source rated at 1 % peak to peak. Stable light output is held to within 1 %. The power supply will regulate line voltage fluctuations of up to $\pm 15\%$ and the light generated will not vary more than $\pm .5\%$. A built-in 9-pin connector can be accessed with an analog input (0-5VDC) to control intensity.

2.2. Software

Several software packages were acquired to assist in image management.

Using this software, and the assistance of an outside contractor, we have developed an integrated analysis tool, which examines the object image in detail and compares it to an acceptable standard.

2.2.1 Measurement Software

A high precision measurement software package that works with off-the-shelf hardware to solve industrial inspection requirements was needed for this application. The software chosen required strong capabilities with pattern matching. Additionally we desired easy application development through Visual Basic. Specific functions needed for this application included pattern recognition and alignment, edge finding, caliper measurement, analysis of arcs and angular regions, grayscale OCR and OCV on any font, blob counting, intensity histogram analysis, and color analysis.

2.3. Housing

Using extruded aluminum and Lucite panels, this 40"X 33" X 70", 400 pound stand-alone test-bed was constructed to be portable and easily maneuverable through any standard 36in doorway. Figure 1 shows the complete system.



Figure 1

2.4 How the System Works

We began this project with the assumption that poor quality watermarks were those that had low contrast. However, after initial experiments it became clear that contrast was not sufficient to describe defective watermarks. Often a defective watermark was characterized by disfigurements in one or more parts of the watermark. To be able to identify these anomalies, many methods for measurement were attempted to collect more detailed information about the images.

- Measuring overall contrast
- Measuring contrast of features
- Using a mask which conformed to the shape of the watermark
- Doing image subtraction of the whole watermark
- Doing image subtraction of individual features
- Applying filters
- Bringing in an outside image analysis expert

Ultimately, we ended up developing our own procedure in which the match of each part of the watermark to a good watermark was determined using pattern-matching recognition. U.S. currency watermarks, by their nature, are noisy images. Two watermarks produced at the same time by the same screen will have almost no pixels matching due to the randomness of the fibers. The pattern-matching recognition method was the only method found to maintain a consistent measurement.

The pattern-matching recognition system uses a neural network to find the key characteristics that describe the pattern. The neural network is not performing a pixel by pixel comparison of the image, but instead is trained to include "acceptable" examples of characteristics. We can set what is an acceptable quality threshold for each characteristic. We can also set what is acceptable for the entire watermark by itself or we could set a threshold for the entire watermark based on the average quality of each of the characteristics in that watermark.

2.5. What is a Neural Network?

Neural networks are a different standard for computing because they are based on a parallel architecture. No programming is involved, as in artificial intelligence. Rather decisions are based on weighted features analyzed by interconnected nodes of simple processing elements using analog computer-like techniques. Neural networks are a form of multiprocessor computer system, with simple processing elements, a high degree of interconnection, simple scalar messages, and adaptive interaction between elements.

Neural networks cannot do anything that cannot be done using traditional computing techniques, BUT they can do some things, which would otherwise be very difficult. Specifically neural networks can form a model from data alone. This is particularly useful when there may be an algorithm, but it is not known, or has too many variables. It is easier to let the network learn from examples.

2.6. Examining Watermarks

The camera is positioned so that the watermark is in a normal portrait orientation. It is positioned above this location at a distance that produces a small (approx 5%) margin at the top and bottom of the field of view. In this way the watermark can be viewed with the maximum pixel resolution, permitting the most accurate possible measurement of watermark quality. Unprinted sheets of currency paper are positioned by hand to inspect the target watermark. The program first reads a live video image of the watermark continuously updating and displaying it on the screen. Every watermark that is inspected is compared to a standard reference. This reference is a synthesized image that was created by enhancing and smoothing a composite of several real watermarks. The boxes shown in figure 1 are the actual areas where pattern matching is performed. The box around the entire image represents an additional feature, titled "face" in the results window. This "Face" feature provides for an overall general appearance of the watermark. An example of this is shown in figure 2.

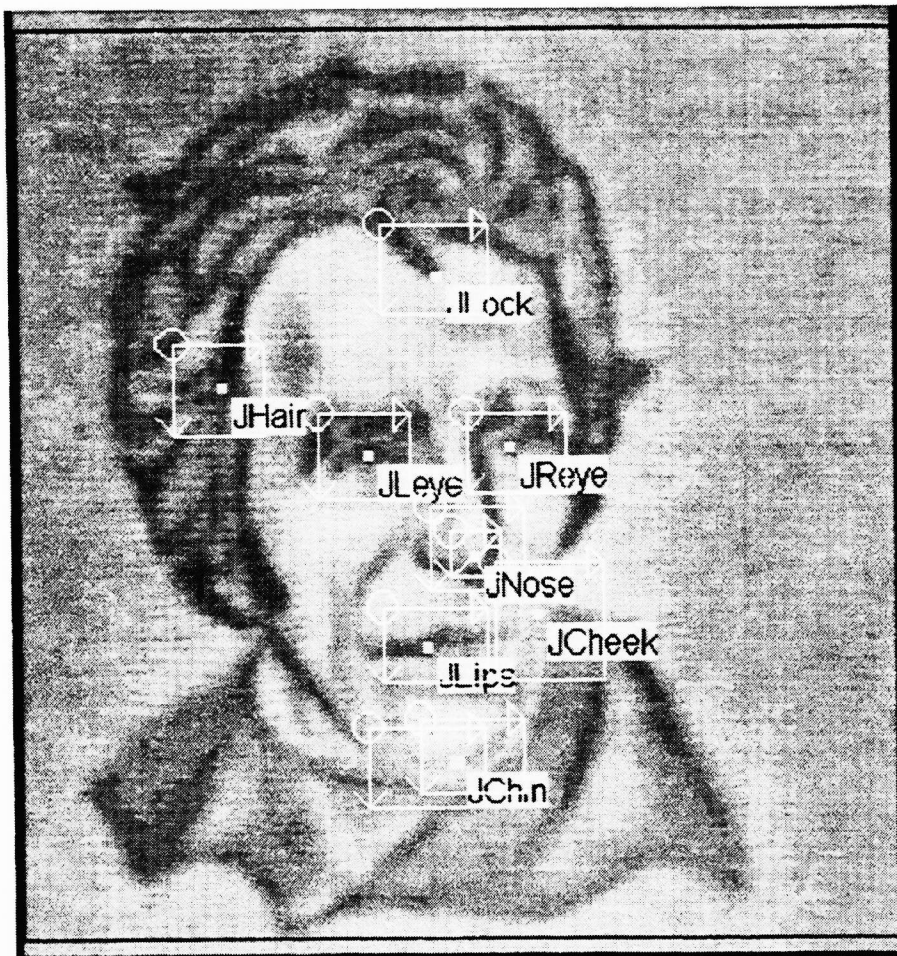


Figure 2

2.6.1 Pattern Matching

The ten areas selected for pattern matching on this image are

1. Face (overall appearance)
2. Lower Chin
3. Chin
4. Lips
5. Cheek
6. Nose
7. Left Eye
8. Right Eye
9. Hair
10. Lock of Hair

In the watermark type (Franklin, Grant, Jackson, etc), ten high-contrast feature areas were selected to represent one tenth of the overall quality score, the Poulsen Measurement Quotient (PMQ). This overall score, is compiled from each of these features. The PMQ is derived by dividing the sum of pattern match score by the number of pattern tools minus any bad features (the sum of 10 scores / 10 - number of bad features). A slight upward curve is applied on an image that has no bad features. A downward curve is applied for individual scores that are low enough to be considered a bad feature. A perfect single pattern match yields a score of one. As the number of bad features increases, the average factors into the equation less. Two bad features are tolerated, but with more than two bad features, the PMQ score is disproportionately affected. After compilation the score is then converted to a ten-point scale and displayed. Figures 3 and 4 show other actual images and results.

Feature Ptn. Quality

Min. Acceptable Score

Measured Score

☐ OK

☐ Low

Feature	Mitch Qlty
Face	0.727
Eye on L	0.622
Eye on R	0.753
Hair Lock	0.718
Nose	0.727
Mouth	0.611
Cheek	0.739
Hair	0.482
Chin on L	0.694
Chin on R	0.770
AVERAGE	0.684

PMQ Score



Figure 3

Feature Ptn. Quality

Min. Acceptable Score

Measured Score

☐ OK

☒ Low

Feature	Mitch Qlty
Face	0.694
Eye on L	0.000 *
Eye on R	0.000 *
Hair Lock	0.715
Nose	0.751
Mouth	0.000 *
Cheek	0.603
Hair	0.664
Chin on L	0.473
Chin on R	0.000 *
AVERAGE	0.650

PMQ Score



Figure 4

2.6.2 Creating the Reference Image

To assure the quality of the composite reference image, a panel of 15 members was established. This panel comprised members representing key components of the currency production process including Technology, Plate Printing, New Currency Design, Counterfeit Deterrence, Quality Assurance, Engraving, and, Research. Each panel member examined unprinted sheets of currency and subjectively selected 15 good watermarks and 15 bad watermarks. For each bad watermark selected, the panel member was required to explain why it was of poor quality. Based on of this data the standard reference image was created. Figures 5-8 show typical examples of watermarks.



Figure 5 - \$5 NCD Poor Quality Watermarks

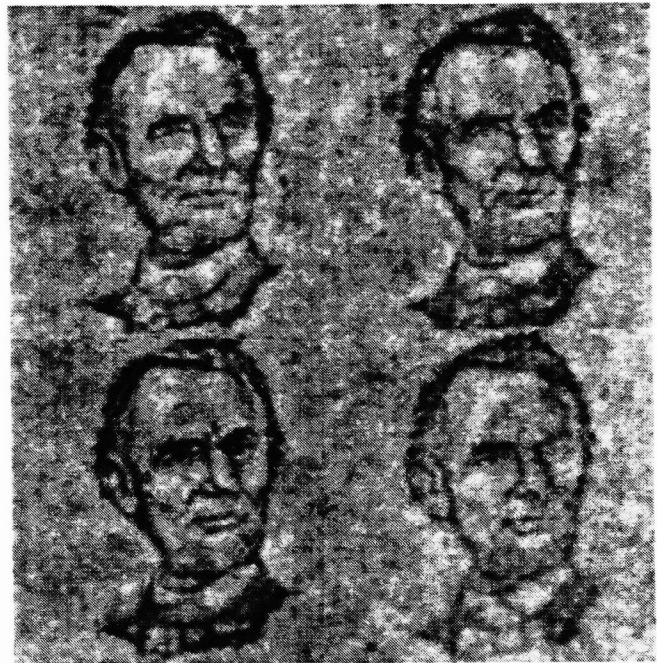


Figure 6 - \$5 NCD Good Quality Watermarks



Figure 7 - \$10NCD Poor Quality Watermarks

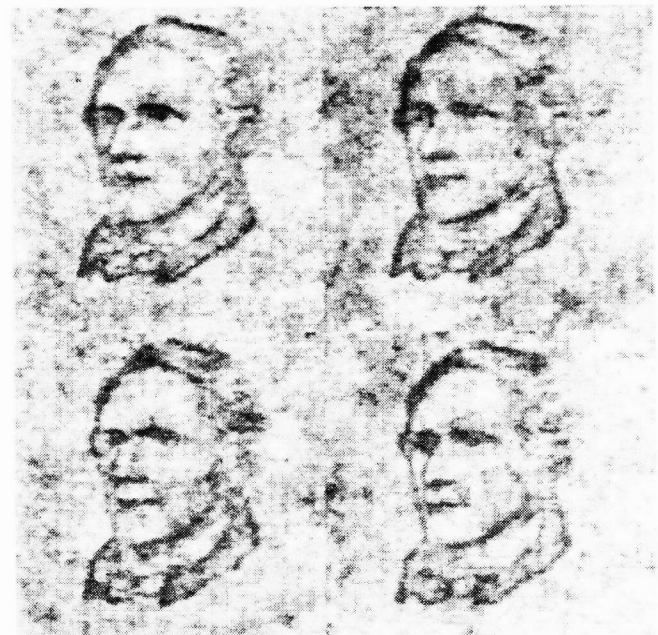


Figure 8 - \$10 NCD Good Quality Watermarks

2.7. Examining Security Threads

Examination and inspection of the security thread is similar to that of the watermark. The camera is positioned so that the security thread is in a normal portrait orientation. Unprinted sheets of currency paper are positioned under the inspection camera using either sheet guides or lines scribed on the inspection table surface. The program first reads a live video image continuously updating and displaying it on the screen. Upon image capture, the edges of the thread are found using a software edge finder tool, and a software caliper determines whether it is within its 4mm-tolerance window. If the thread is found and it is in its correct location, then the data file reflects this information. Figure 9 shows an example of the inspection area using edge finder and caliper software tools.

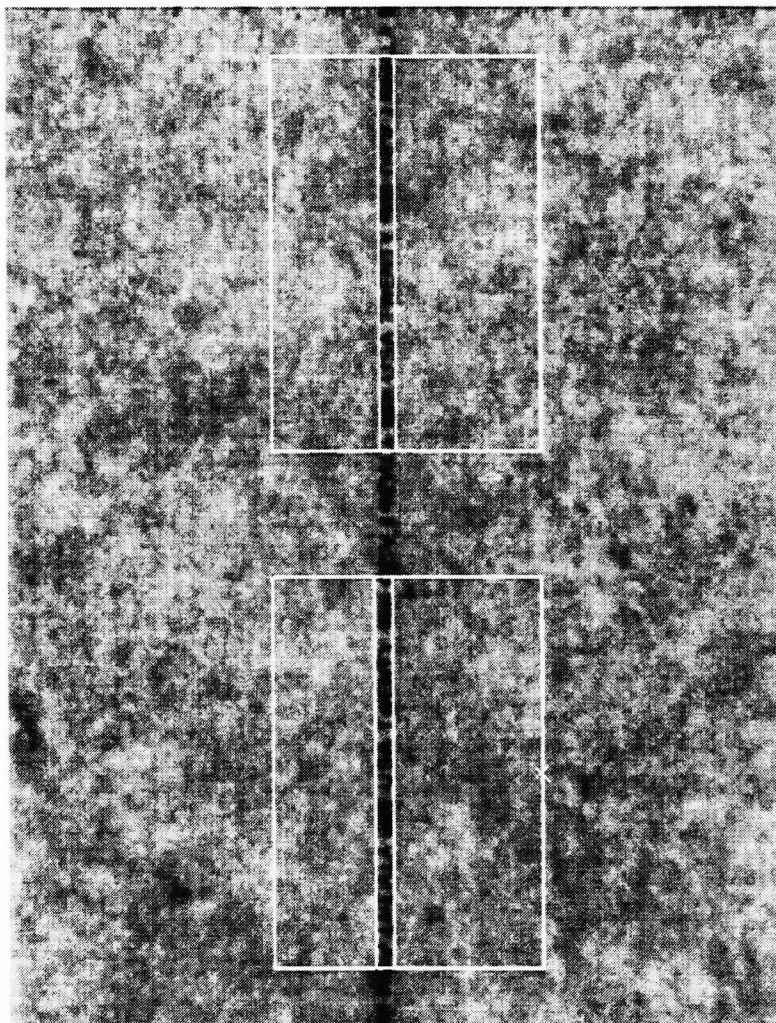


Figure 9

2.10. Conclusions

This system has the ability to identify characteristics of a watermark that are most commonly deformed. It does a very good job of passing the watermarks that are above the threshold of acceptability while failing the watermarks below the threshold of acceptability. The security thread examination shows when the thread is of an acceptable quality and is within the limits of acceptable dimensional parameters.

Using this system the BEP has been able to implement a sampling plan for unprinted currency sheets. By examining the resultant data, quality can be controlled and feed back can be given to the paper manufacturer. With this watermark and security thread transmissive inspection system, we have the ability to maintain uniformity of these features, as required for all U.S. currency.

2.11. Next Steps

Presently unprinted currency sheets are positioned by hand to capture each image. We are developing a system, which incorporates motion control servo motors in the x-y plane that will precisely position the cameras in an exact location on the sheet. Simultaneously thread and watermark images will be captured and the data will then be automatically analyzed and stored. The system will be self actuating and position the cameras in the proper location on the next note. This process will repeat 32 times until every image on the sheet has been captured. From this data we will not only have the ability to compare image quality we will also be able to measure position of the thread and watermark relative to the sheet. Additionally we know measurements of the thread and watermark as they vary from note to note. The automation of this process will enable us to collect more data, from a larger sample, in a shorter period of time.

3. Semi-Covert Machine-Readable Feature

A need existed to examine a semi-covert machine-readable feature. To satisfy this need, the BEP has developed a real-time, online inspection system capable of monitoring this feature, which is based on the application of specific inks applied in denomination-specific patterns in precise locations throughout the sheet. This system performs an inspection on the specific pattern, which is outside the visible spectrum. The system reports failures for both printed and substrate areas, provides real-time reject information that is output to the operator; this system also has the ability to reject an individual sheet for failure.

3.1. System Information

This application uses an 8 bit monochrome tethered head camera that provides for increased sensitivity and low light imaging capabilities. We have removed the standard cut filter from this camera and installed a pass filter to capture the light within the target range.

The host computer is a standard 400MHz Pentium II PC with 128mb of RAM. This host computer and other elements of this system were chosen because they are readily available, off-the-shelf, and quickly interchangeable. Each of these items can easily be acquired and replaced in the event of failure.

Integrated within the host computer is a frame grabber board. This board provides for digital I/O capability to enable the light bar and voice module through the use of programmable "call" statements. We were required to install additional triggering hardware for all key components in this application. Integrating this signaling required significant interrogation of the existing inspection system.

Two external signaling devices were installed to inform the plate printer of the system status. The system status is displayed visually from a color-coded signaling light tower that indicates sheet acceptability according to the following scheme.

Green	Acceptable
Yellow	Warning (accepted)
Red	Reject
White	Calibration Mode

Through these visual cues the operator can monitor this ink feature while simultaneously making press adjustments. The operator receives feedback on a sheet by sheet basis to assure that contamination situations do not occur and that the quality of this feature is maintained. An audible signal has also been incorporated to signal system conditions. If at anytime the operator is out of the systems visual range, a digital voice recording serves as an audible alarm to alert an error/reject condition. The recorded message provides information that includes which area on the sheet a failure has occurred.

The image analysis is performed by commercially available machine vision software. The user interface and output software was developed in house with assistance from Agris-Schoen machine vision consultants. This system performs 100% inspection at no less than 2.4 sheets per second. This system inspects for specific types of ink transparency in a specified range of the light spectrum.

3.2 Press Integration

U. S. currency is printed using the intaglio process on printing presses manufactured by Giori-DeLaRue. The existing on-line print inspection system incorporated with these presses is the Giori Nota-Save. For the machine-readable feature, this new inspection system, which operates outside the visible range, has been integrated with the existing print inspection system. To access the appropriate segment of the spectrum that is required to perform this inspection, we are required to capture an image in a 20 μ sec time frame that is controlled by the Nota-Save. The Nota-Save sheet trigger signal is intercepted, processed and used by both systems. This system has been in use for several months.

3.3. Operator Interface

This on-line inspection system is completely controlled by a track ball and pull down menus; no keyboard interface is required. The operators' interface monitor displays a captured real time image of each currency sheet. An overlay image unique for each denomination that displays the zones available for inspection is completely independent of the inspection process and can be accessed, as needed, without interfering with the currency sheet examination. Figure 10 shows the operators console for this application

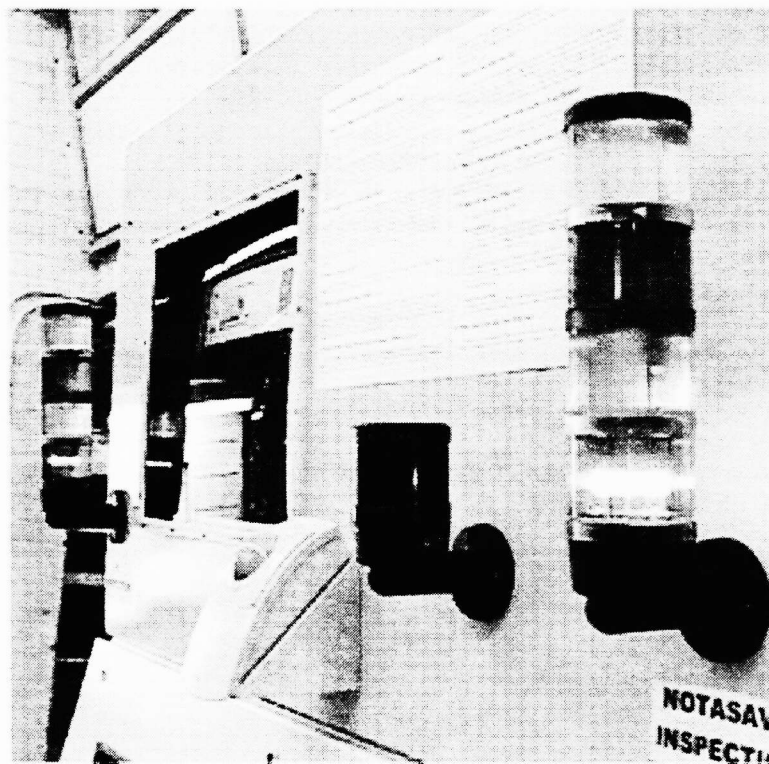


Figure 10

After make-ready, the calibration process is begun. A separate off line inspection is performed on a single currency sheet to assure that the ink pattern is in the correct location and that no ink contamination is occurring. During calibration, 80 currency sheets are recorded, and each zone within the currency sheet is isolated and measured. The data from these 80 currency sheets are used to derive "Good Measurement Range" values. Each zone on the sheet has its own minimum and maximum range. The operator's display will show the darkest average grayscale as it correlates to the minimum values. Also displayed is the brightest average grayscale as it correlates to the maximum values.

This inspection system was designed to allow for tuning adjustments. Four individual slide bars are used as an operator interface. One slide bar represents the minimum measurement while the other represents the maximum measurement for both types of ink. These slide bars correlate to a maximum deviation of 10%. The maximum deviation is measured from values learned during the calibration process. The complete range of tuning is minimum calibration minus 10% to maximum calibration plus 10%. The default tolerance setting is a range of: minimum -5% to maximum +5%.

3.4. Conclusions

The installation and on-line use of this system has enabled the BEP the ability to manage the quality controls necessary in incorporating this feature into all new currency designs. This system provides instant feed back to the press operator, to ink contamination situations and providing feedback on the quality of this feature in a real time environment. On a sheet-by-sheet basis this system provides for the ability to reject printed work that does not meet the established acceptability criteria. The implementation of this inspection system will have significant long-range effects on the use of United States currency as it relates to this machine-readable feature.

3.4. Next Steps

Through the development of this system we have found several problem areas which are connected with hardware integration issues. The next generation of this system as been refined and streamlined through the knowledge that we have gleaned in this process.

We have found a timing problem that causes an invalid image capture approximately once per minute. This spurious image is trapped and analysis is not performed on that specific image. The source for this invalid image has been traced to the image capture board. The replacement of this image capture board would require a substantial amount of man-hours and rewriting the system software. As a practical resolution to this situation we are testing a faster camera with a 5 μ sec asynchronous trigger. This faster speed will assure that images are captured within the 20 μ sec strobe light window and eliminate the problems encountered to date.

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